tional water development schemes. Yet more is known about the costs and effectiveness of gray infrastructure in a development context.

Economic efficiency, typically used to estimate the cost of gray projects, can lead to underestimates if changing environmental, economic, or social conditions are not taken into account (*9*). For example, although large dams may produce energy and protect the nearby populace and fields from floods, an estimated three out of four dam projects have cost overruns, on average, 96% greater than estimated (*10*). Underestimates are compounded if the burden of potential remediation costs is not considered, such as removal of contaminated sediments.

Gray water infrastructure is not always reliable; for example, levees lead to increased flood levels downstream (*11*). Levees can give a false sense of security that favors human encroachment in floodplains and, consequently, more flood damage than when levees are absent.

Evaluations of the economic benefits of green options that consider a range of social and environmental uncertainty, have, for example, ranked wetlands, tidal marshes, and coral reefs as particularly valuable (*12*). However, few studies have compared costs of green versus gray approaches, e.g., questioning the wisdom of replacing mangroves and corals with seawalls and breakwaters in peninsular Malaysia (*13*).

RESEARCH FOREFRONTS. The developed world has studied urban green infrastructure, but more research is needed to predict the performance of a network of structures within different environmental contexts (*14*). Even when existing finance, risk, and investment theories can be combined to compare gray and green (*15*), critical biophysical performance data are needed.

A new generation of "sociohydrologic" models is exploring social acceptability and biophysical trade-offs for different configurations of infrastructure. Testing and validation using case studies and data on social and biophysical drivers and ecological constraints will be required for broad application (*16*).

Most forest restoration programs are based on the assumption that forest area is a proxy for ecosystem services based on rainfall and water use. Reforestation can provide water regulation benefits by reducing streamflow variability and peak flows (*17*) and, in some cases, can enhance soil water storage (*4*); yet water flows that result from reforestation in larger tropical basins are rarely quantified. Modeling studies suggest that large-scale [i.e., >10^4 to 10^5 km^2 (*18*)] deforestation can reduce rainfall through changes in the surface energy balance and evapotranspiration; this effect, however, depends on the geography and other factors (*19*). Work is still needed to determine whether large-scale forest restoration could become a valuable approach to increase rainfall and water yield.

ADOPTION. When reliability needs are high and/or tolerance for failure is low, gray water infrastructure probably represents the most effective approach to meeting the needs of developing countries. However, gray infrastructure can result in substantial damage to ecosystems and livelihoods; thus green infrastructure may represent a safer, more conservative pathway. The multiple benefits of green infrastructure are not broadly recognized, and the lack of cost-benefit data increases perceived risks. However, ongoing geographic shifts in agricultural production, needed growth in developing countries, and uncertainty about future climates provide an opportunity to renegotiate how we quantify sustainable infrastructure over long periods and express trade-offs between environmental and economic parameters (*12*). ■

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Built infrastructure is essential

By **Mike Muller,**[1*] **Asit Biswas,**[2,3] **Roberto Martin-Hurtado,**[4] **Cecilia Tortajada**[2,3]

Built water infrastructure supported the evolution of all human societies and will remain an integral part of socioeconomic development and modernization. Some postindustrial societies not only seek to "preserve" existing aquatic ecosystems in their otherwise transformed landscapes but also insist that others do the same. They suggest that "green infrastructure" can provide "equivalent or similar benefits to conventional (built) 'gray' water infrastructure" (*1*).

WATER DEBATE SERIES

Fast developing countries have a different perspective. For them, built infrastructure underpins "water security": enough water of adequate quality, reliably available to meet health, livelihoods, ecosystems, and production needs, as well as protection from water's destructive extremes (*2*). Their challenge is to enable an expanding global population, seeking a better quality of life, to determine the nature of their new environment, not simply to preserve the old.

21ST-CENTURY CHALLENGES. By 2050, water systems will have to support a global population of 9.6 billion, up from 7.2 billion in 2013 (*3*), most in expanding cities far larger than those of Europe and North America. More people and property will need infrastructure for services far beyond the capacity of "green infrastructure," based on natural ecosystems, to provide.

The OECD estimates (*4*) that global water abstraction for domestic and industrial purposes will more than double by 2050. Improved efficiencies may help (a 14% reduction in agricultural demand is forecast on this basis), but the world in 2050 will need more water infrastructure.

Large conurbations have long exceeded the capacity of local sources, and extensive infrastructure is required to capture, store, transmit, treat, and distribute water to them. Even a mature society like the USA needs to invest almost $400 billion in its existing built infrastructure between 2011 and 2030 just to sustain drinking water supplies (*5*). The urban populations of China and India are expected to grow by 292 million and 404 million people, respectively, between 2014 and 2050 (*6*), with Africa and Latin America not far behind. These populations have access to better technologies and information, but their climate variability and extremes limit the potential contribution of "green" infrastructure and require built infrastructure to achieve water security.

Interventions needed to achieve water security depend not just on local specifics of topography and climate but also on institutional capacities, policies, economics, and politics. Global warming will reduce flows from water stored in Andean glaciers. So trans-Andean transfers through short tunnels from high-level dams in the Amazon and Orinoco basins are logical responses for growing cities along South America's arid Pacific coastal region.

"For [fast-developing countries], built infrastructure underpins 'water security'"

The 10 major rivers flowing from the Hindu Kush Himalayas underpin water, energy, food, and ecological security for 1.3 billion people. Only carefully judged infrastructure investments can provide water security for, for instance, the 50 million people in Bangladesh vulnerable to the calamitous coincidence of river flooding and storm surges.

SHIFTING CHALLENGES. Despite obvious needs, water projects are often opposed because they threaten poor people's livelihoods and the environment (*7*). In societies with water security, this opposition reflects changing social priorities. But "green infrastructure" often fails to achieve its goals.

In Britain, proposals to reduce sewage spillages into the Thames river using "green engineering" techniques were "not considered to be technically feasible" (*8*, *9*). Instead, a massive 25-km tunnel is being built to contain contaminated stormwater and divert it for treatment.

Controversy surrounded South Korea's Four Rivers Restoration project; although promoted as a "green economy" project, it was criticized as "an ecological disaster" (*10*). Yet only a package of dams, dykes, and hydropower plants could reduce deadly flooding and sustain land and water availability.

Environmental concerns halted a century of infrastructure development in Spain. A transfer from the Ebro River to water-short areas, proposed by the 1998 National Hydraulic Plan, was later rejected on economic, environmental, and political grounds (*11*). But when drought struck in 2008, Barcelona had to import water by ship, and farmers refused to pay for desalination plants, built as an alternative. Australia suffered similarly, and both countries are now analyzing the limitations of green infrastructure and the "dams versus desalination" dilemma (*12*).

Rapidly growing developing countries cannot afford risky experiments or high-cost alternatives. Although potable water needs are being met in most urban areas, sanitation and wastewater treatment are daunting tasks requiring even more investment.

These countries have followed precedent and public preferences, giving initial priority to infrastructure for water supply, irrigation, energy, and flood protection, followed by investments in wastewater management and, finally, other environmental improvements.

This sequence makes sense, given the vicious cycle of water insecurity, in which national economies cannot support the infrastructure investments needed, in part, because water security has not yet been achieved (*13*). In Africa, demands from water-secure communities elsewhere for green alternatives have delayed economic growth and social development (*14*). Economic water scarcity (*15*) is exemplified by the city of Cherrapunji, India, which, despite an annual rainfall of 12,000 mm, suffers severe water shortages during dry months because of inadequate storage.

CHANGING CLIMATES AND PRIORITIES. Over time, societies' needs for water infrastructure change. The Netherlands, whose existence depends on built water infrastructures, can now make "more room for the rivers," including flooding reclaimed polders, because agricultural intensification reduced the demand for agricultural land.

China's Three Gorges Dam symbolizes the infrastructure required to sustain prosperous large societies in the 21st century. It had social and environmental costs but protects millions of people from floods; supports economic development through improved inland navigation; and generates more emission-free electricity than most European countries (*16*). It also helps to integrate wind and solar power into China's electric grids, building resilience while mitigating climate change.

In this Anthropocene world, the primary concern should be to ensure that infrastructure interventions are part of a broader process of "ecological modernization" (*17*) that meets people's aspirations within an altered but sustainable and socially acceptable ecological framework. ■

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